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AIR VORTEX WAKES AND THEIR CAUSE

Society of German Air Traffic Controllers

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29

Table of Contents

	Page
Foreword	iii
Air Vortex Wakes — How do They Arise?	1
A Handful of Formulas	2
And a Pinch More of Theory	5
What Happens If . . . . ?	8
a) Parallel flight between the air vortex wakes	8
b) Parallel flight through an air vortex wake	9
c) Flight perpendicularly or obliquely through both air vortex wakes	10
Ground Rules for Avoiding Air Vortex Wakes. Ground Rules and Illustrations.	11
Special Flight Safety Procedures for Avoiding Air Vortex Wakes	19
Conclusion	24
Bibliography	25

Abbreviatons Used in the Text:

π = circle factor (3.14159 . . .)

b = wing span

v = flight speed

v_A = downwash velocity

G = weight

ρ = air density

ABSTRACT. The dangers of air vortex wakes caused by jumbo jets such as the B 747 to air traffic is discussed. The effects of these wakes on other aircraft is described and safety measures are presented.

FOREWORD

The concept of "air vortex wakes" is receiving increasing importance with the expanding use of modern large aircraft.

The strength of the invisible air vortex wakes caused by aircraft depends on the flight weight, among other factors. The danger to air traffic, especially in takeoff and landing, increases considerably with the use of heavier and heavier aircraft.

The B-747 has been in commercial air traffic since the beginning of 1970. Other commercial aircraft of the "third generation" like the McDonnel Douglas DC-10, the Lockheed L-1011 Tristar and the Lockheed L-500 will soon be part of the everyday picture at international airports. Existing publications of the International Civil Aeronautics Association (ICAO) scarcely mention air vortex wakes. The footnotes on this subject in various ICAO documents do not do justice to the dangers caused by air vortex wakes.

For this reason, the Society of German Air Traffic Controllers considers it essential to provide greater publicity for the concept of air vortex wakes with the present brochure.

Society of German Air Traffic
Controllers

- The Board of Directors -

<u>Air Vortex Wakes — How Do They Arise</u>

The wings, which provide lift for the aircraft, at the same time produce invisible air vortex wakes, in the following way: /2*

From movement through the air, a decreased pressure is produced above the wings, and simultaneously an overpressure under the wings. These produce the lift. This pressure distribution is not homogeneous. The underpressure on the upper side becomes weaker as it approaches the wing tips, while the overpressure on the underside reaches its maximum at just this point. A possible pressure equilibration always goes on along the shortest path, and thus around the wingtips. This sets the air at these locations into rotating motion in the form of two oppositely rotating cones of air rolling off to the rear.

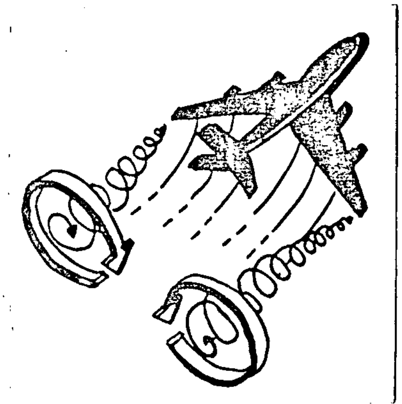

Figure 1

The rolling process in these vortex wakes usually ends at a distance which corresponds to about two to four times the wingspan. The core of the vortex is displaced from the wingtip to the center by about 15% of the wingspan. /3

The air in the vortex wakes rotates about this core, in which the tangential velocity is equal to zero. It increases outward, so that the greatest danger appears at the boundaries of the vortex wakes. According to measurements of the American

*Numbers in the margin indicate pagination in the original foreign text.

air travel authority, NASA (National Aeronautics and Space Administration), the rotational velocity of the air in these vortex wakes can reach values of up to 80 degrees per second. Values determined for the movement of the air in vortices at a distance of 10 feet (3 meters) from the core were 24.5 feet/second or 1,470 feet/minute (DC-7 aircraft design) and 51.7 feet per second or 3,102 feet/minute (B-707 aircraft design, with a takeoff weight of 300,000 pounds).

NASA has also determined the velocities with which the vortex wakes sink down. These were 195 feet/minute for the DC-7, and 306 feet/minute for the B-707. These sinking velocities of the air vortex wakes decrease near the ground until they spread out to the side at a height of about half the wingspan, normally with the wind.

According to previous study results, wind speeds up to 6 knots have hardly any effect on the rotational, turbulence, and sinking velocities of the air vortex wakes. Light sidewinds cause only a displacement with the wind, without altering the characteristic features. Only wind speeds of 10 knots and above lead to rapid breakup of the vortex wakes. Exact numbers relating to the resistance of the wakes to the wind are not now known.

A Handful of Formulas

Four forces act on an airplane in flight, and determine its /4
direction and velocity:

Lift, drag, thrust, and weight.

The lift and weight are of particular importance in the origin of air vortex wakes.

With airplanes, a downward-directed air stream arises as a reaction to the pressure acting on the underside of the wings (Figure 2).

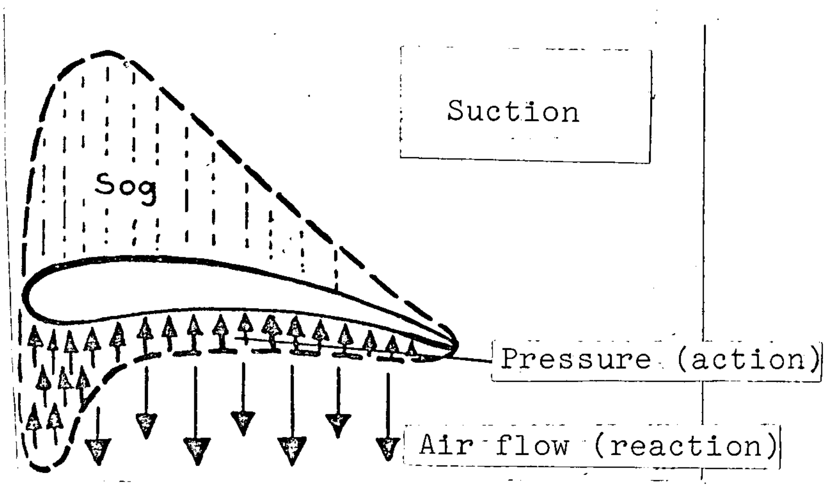

Figure 2. Pressure-suction ratio and downward-directed air stream at the wing

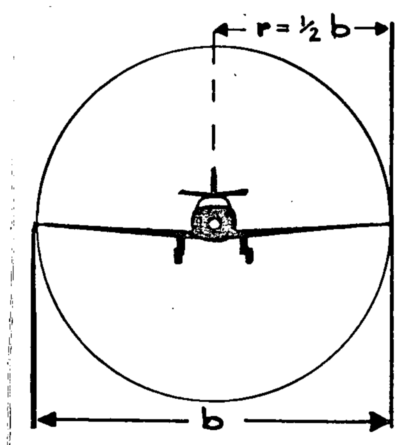

Figure 3. Circular area with the radius of half the wing span (Front view)

Now, if we consider the air flowing around the wing surfaces, we can express its order of magnitude as follows: /5

$$\text{Circular area } F = \frac{\pi \cdot b^2}{4}$$

The amount of air which flows past the wings of an airplane in flight corresponds in Figure 3 to the volume of a cylinder with the radius 1/2 b and the length v; therefore

$$\text{Volume} = v \cdot \pi \cdot \left(\frac{b}{2}\right)^2$$

As this volume is also dependent on the density ρ of the air, the formula above must be supplemented as follows:

$$\text{Volume} = \rho\ 1\ v \cdot \pi \cdot (b/2)^2$$

The lift A of an airplane must accordingly be qqual to the formula for this cylindrical volume multiplied by the downwash /6 velocity v_A, as follows:

$$\text{Lift } A = \rho \cdot v \cdot v_A \cdot \pi \cdot (b/2)^2$$

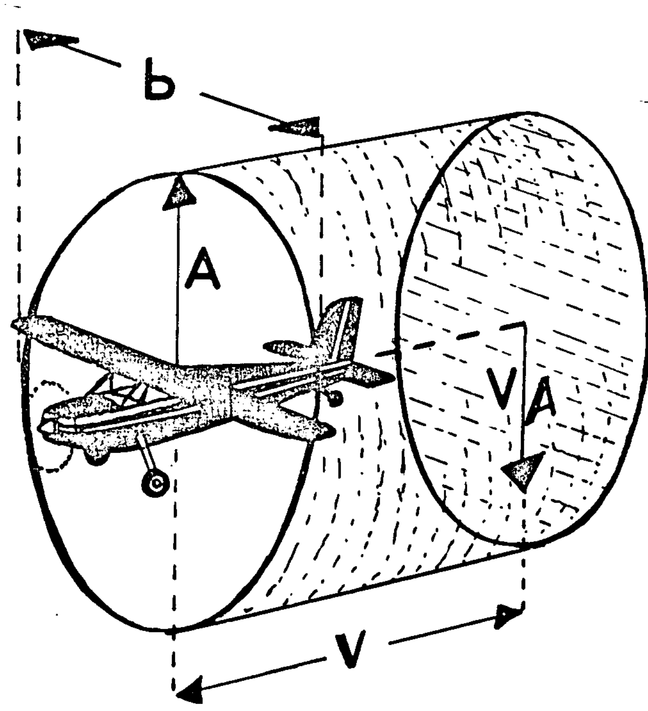

Figure 4. Volume of the amount of air flowing around the wings

The magnitude of the lift A is determined essentially by the weight factor (G), by which we mean gross weight. Now if we replace the factor A in the lift formula above by the factor G, we get

$$\text{Weight } G = \rho \cdot v \cdot v_A \cdot \pi \cdot (b/2)^2$$

Now, if we solve this formula for v_A (downwash velocity), we get

$$\text{Downwash velocity } v_A = \frac{G}{\rho \cdot v \cdot \pi \cdot (b/2)^2}$$

or

$$\text{Downwash velocity } v_A = \frac{4 \cdot G}{\rho \cdot v \cdot \pi \cdot b^2}$$

Comment: This mathematical description is only intended to show the influencing factors. It was compiled to be generally understandable, and so makes no claim to scientific proof. /7

And a Pinch More of Theory

The mathematical relation which determines the order of magnitude of the air vortex wakes was explained briefly in the previous section. The deciding factors, then, are:

a)	total weight (including payload) of the aircraft	G
b)	wingspan	b
c)	flight speed	v
d)	air density	ρ

Total weight G: The greater the total weight of an airplane — its own weight plus its load — the higher the lift must be to keep the plane in the air. The increase of the pressure-suction ratio below and above the wings which is needed to increase the lift strengthens the spinning and rolling process of the turbulent air at the wingtips. In other words: as long as the plane is still on the ground — i.e., the weight is supported by the landing gear — the lift and, thus, the strength of the air vortex wakes is zero. Thus, the air vortex wakes appear only at take-off at the moment of liftoff. On landing, the production of vortex wakes stops as soon as the weight of the plane rests entirely on the landing gear.

Wingspan b: The downwash movement, and with it the strength of the air vortex wakes, is inversely proportional to the square of the wingspan. Therefore, the greater the wingspan of an aircraft, the less the downwash movement and the air vortex wakes behind the plane. Conversely, shortening the span has the inverse effect: downwash and vortex wakes become greater! /8

Until recently, then, it was feared that the SST aircraft (SST = supersonic transport) such as the Concorde would raise particularly great problems in this respect, because they operate with both high flight weight and small wingspan (Concorde wingspan: 25.55 m). At least for the approach phase of the Concorde, something different can be said, according to wind tunnel studies by the British Aircraft Corporation (BAC).

It was discovered that, after about 5/8 mile, the air vortex wakes showed only 10% of the strength which they had had at the wingtips. It also appeared that the vortex energy is, to be sure, very high when it separates from the wing. But it becomes exhausted considerably faster than with conventional airplanes because of the high initial energy and the small distance between the individual vortex trains at the wingtips. Because of their smaller extent, the vortex trains of the Concorde offer less danger to a following airplane than those behind a B-747 (Jumbo Jet). The Concorde vortex wakes rapidly reach the so-called "intermixing" point. Here mutual energy consumption sets in, and causes the vortex to break up. For conventional airplanes, the intermixing point is four times as far away as for the Concorde!

The sinking rate for the Concorde vortex wakes is three times that for the B-707 and twice that for the B-747. But the breakup begins, through the intermixing point, after a fourth of the distance for the B-707 and 747. Therefore, the British Aircraft Corporation, Ltd., concludes that separation between the Concorde and a B-707 need not be increased, in contrast to a B-747 (Jumbo Jet). /9

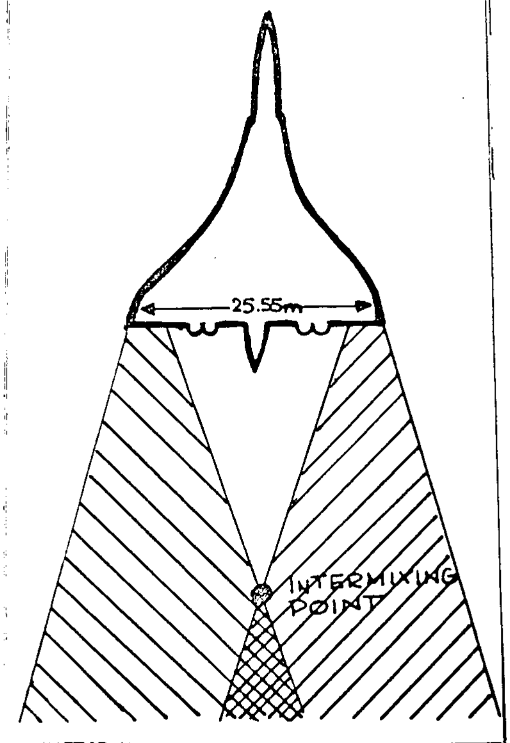

Figure 5

Flight speed v: The assumption that weaker air vortex wakes would result from a decrease in flight speed is incorrect. In contrast, the lift must be increased at low flight speeds in order to keep the plane in the air at all. The result is an increase of the downwash movement and simultaneously of the air vortex wakes. /10

A glance at the formula for calculating the downwash motion provides mathematical confirmation: the greater the value for speed in the denominator, the smaller the result for the downwash rate.

Air density $\boxed{e}$: This is also a factor which can affect the downwash movement and the air vortex wakes. Its effect is inversely proportional. In other words: the lower the air density, the stronger the vortex wakes! As all the airports in the Federal Republic have a low elevation (height above standard zero) and thus have a relatively high and constant air density, the factor $\boxed{e}$ can be neglected here. Only increasing flight altitudes and correspondingly decreasing air densities act to increase the air vortex wakes. This effect is compensated by higher flight speeds at greater altitudes.

What Happens If . . . . ?

The previous sections have explained how air vortex wakes are formed, what factors affect them, and where they appear. Now we shall explain, with three examples, what happens if a plane flies into the invisible vortex wake region and what dangers lurk there.

a) Parallel flight between the air vortex wakes /11

If one plane follows another on about the same course, it can get into the danger region produced by the vortex wakes of the preceding plane, especially if its own flight altitude is less. In the worst case, the plane flies parallel to the two vortex wakes, exactly in the zone of the air moved downward by the two vortex wakes. Then it is struck simultaneously by the downward-directed intensity of both vortex trains (Figure 6).

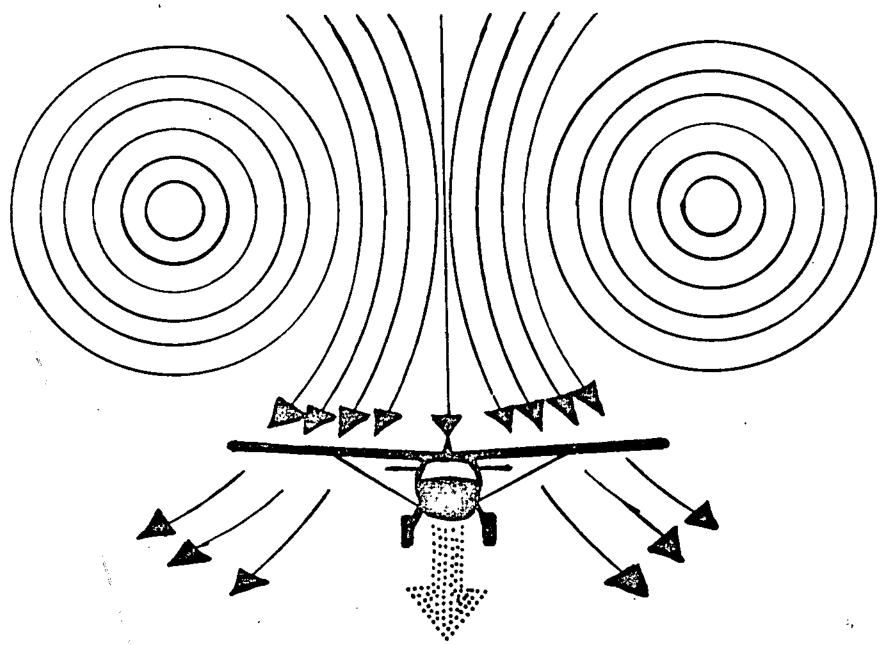

Figure 6

The result is a reduction of the vertical movement of our own plane. The strength of the air down-flow in the vortex wakes can exceed the climb rate of a plane. This process is especially dangerous at low altitudes and at reduced speeds (landing approach, landing). The danger increases even more if an inexperienced pilot is confronted with it. /12

b) Parallel flight thorugh one air vortex wake

Two vortex trains are not required for danger to occur. Even one vortex train is enough! If a plane, flying parallel to the two vortex trains, flies into only one of them, the plane is brought into a rolling process. This has the following causes: As the air in the vortex wake is rotating, the force of the rotating air acts on one wing surface from the bottom upward and on the other wing from the top downward. If the force of the rotating air in the vortex wake is greater than the compensation which can be applied by corresponding aileron control movements, then the plane will roll.

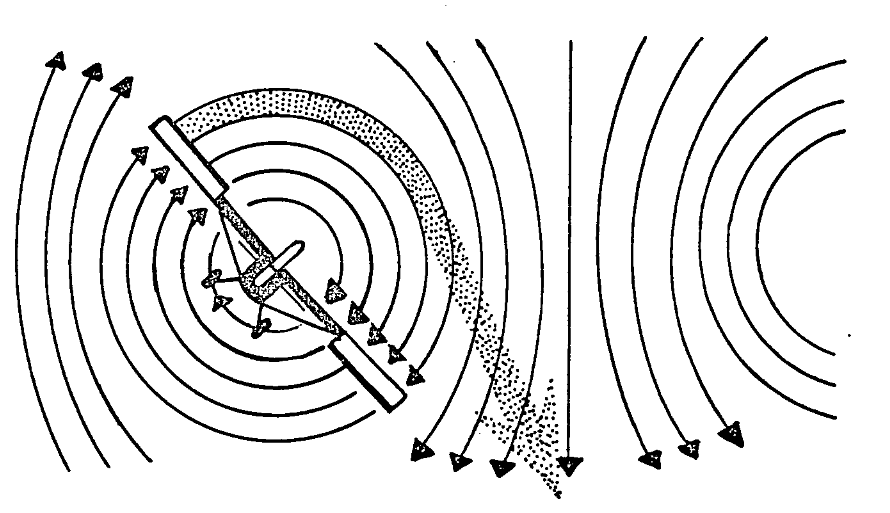

Figure 7

The lower the flight speed, the smaller are the forces acting on the ailerons. This, again, decreases the possibility of compensating for the rolling motion caused by the vortex wake. /13

c) Flight perpendicularly or obliquely through both air vortex wakes

Another possibility of being endangered by air vortex wakes appears on perpendicular or oblique flights through the vortex train zones of another plane.

In this case, the plane, crossing the first vortex wake, first enters a zone of upward-directed air and then, after passing the center, enters downward-directed air. The downward trend continues because the plane remains in downward-directed air as it flies into the second vortex wake, before it enters an upward motion after flying through the center of this wake.

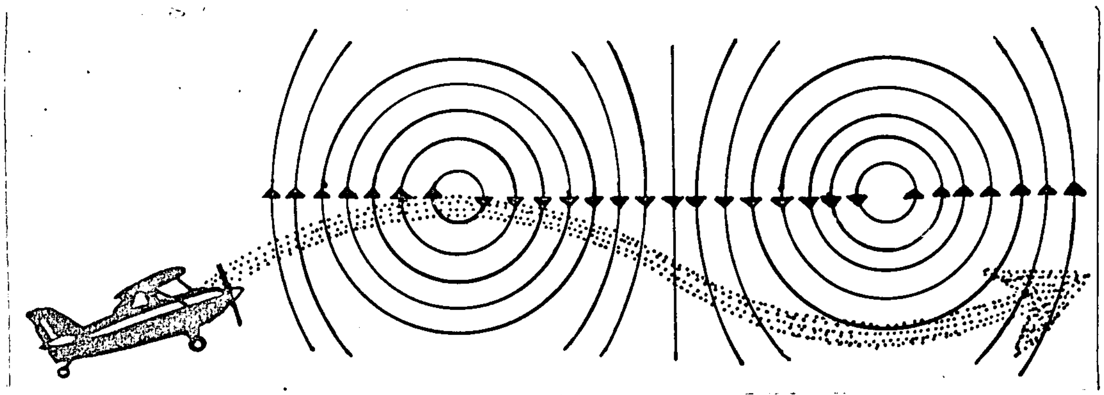

Figure 8

The results, in all, are a series of opposing strongly limited gusts in the vertical direction. The forces acting on the plane and the attempts of the pilot to oppose these forces with appropriate control movements can in the extreme case lead to exceeding the load limits of the airframe. The flight speed also has a role, because the greater the flight speed, the greater the stress on the frame. /14

Ground Rules for Avoiding Air Vortex Wakes

In the meantime, the reader will have understood what a considerable danger the air vortex wakes are for air traffic. But there is much which can be done to prevent the danger. The following ground rules and illustrations are intended to help avoid accidents:

Vortex wake sinking characteristics

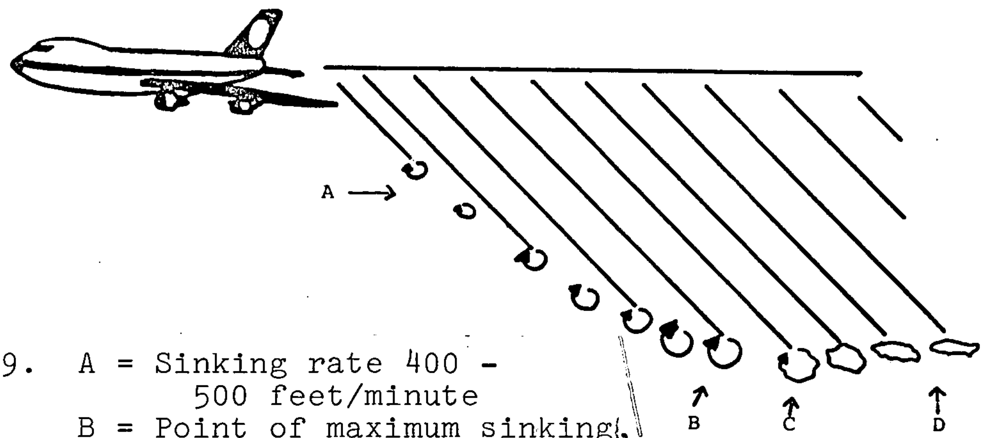

Figure 9. A = Sinking rate 400 - 500 feet/minute
B = Point of maximum sinking, 800 - 900 feet
C = Beginning of breakup
D = Smaller remaining residues

One should fly on or above the course of heavy jets. If necessary, change course to avoid the region behind and below the jet.

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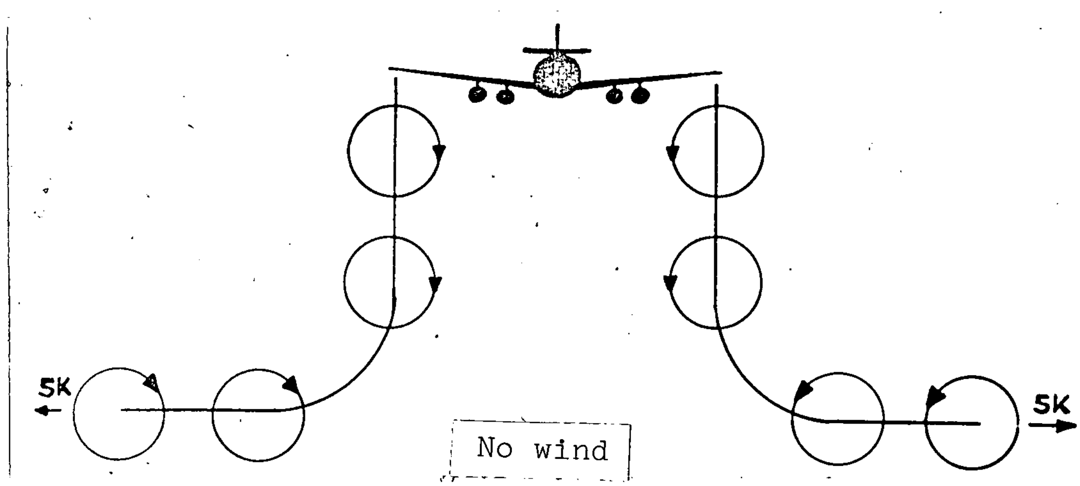


Figure 10. If air vortex wakes sink to near the ground, they tend to spread out laterally across the ground at a speed of about 5 knots

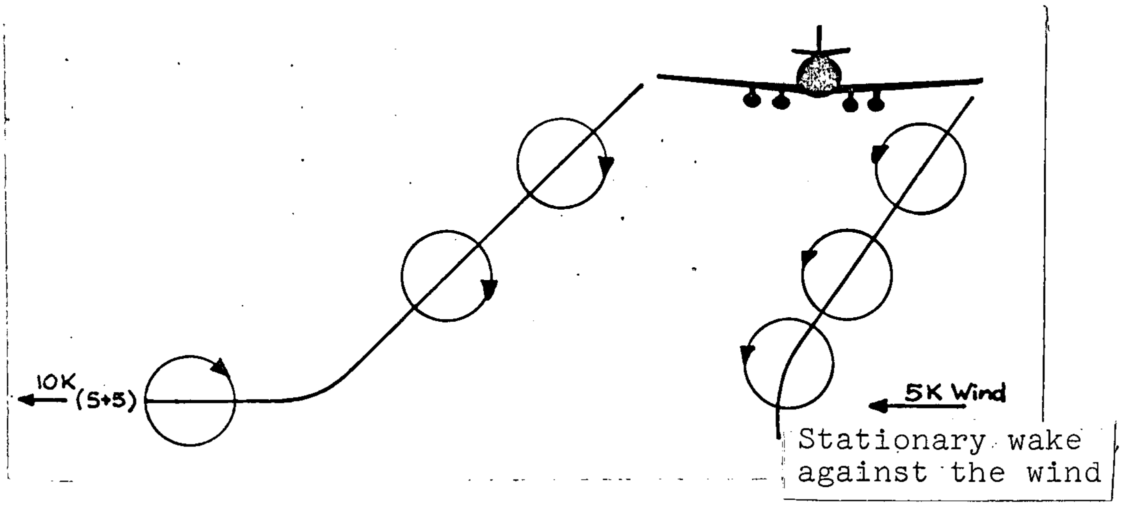
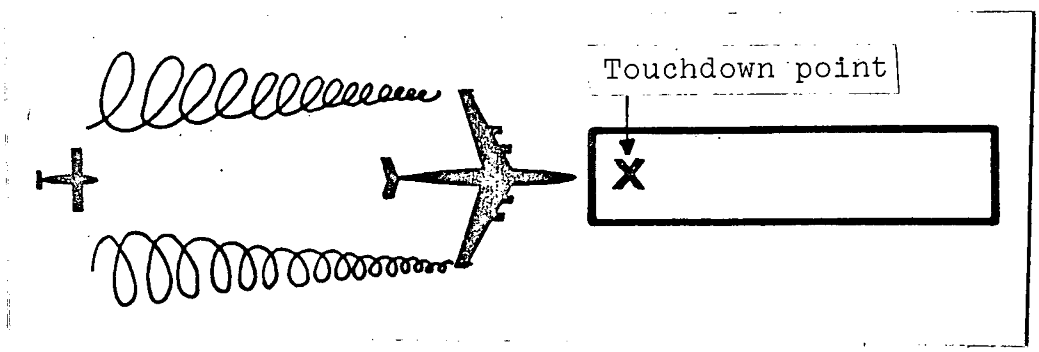


Figure 11: A sidewind component decreases the spread of the wake against the wind and increases the spread of the other with the wind. This can leave the wake directed against the wind in the touch-down zone and allow the other to drift faster to a parallel runway



/16

Figure 12. Tower: You are second to land. Follow the Lockheed C5A on final approach. Be careful of air vortex wakes!

Pilot: Stay on or above the flight path of the jet; note its touchdown point, and land beyond it...

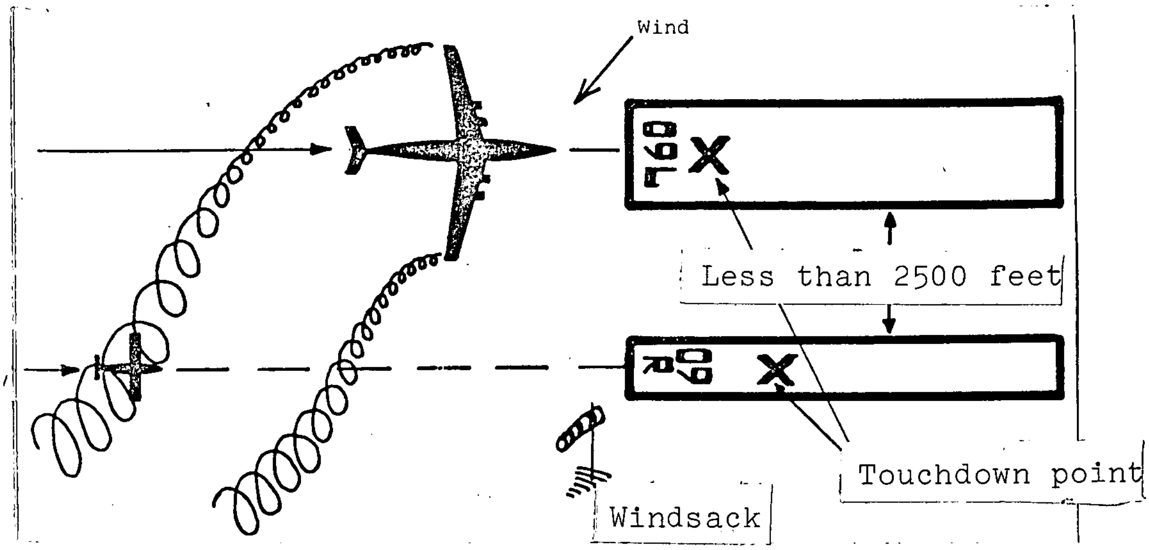


Figure 13. Tower: You are free to land, runway 09R. Watch out for air vortex wakes from the B-747 on final approach, 09L.

Pilot: Going upwind, be careful of possible drift of the vortex wakes to your own runway. If possible, request the other runway. Otherwise, stay on or above the jet flight path; note its touchdown point, land abreast of and beyond its touchdown point

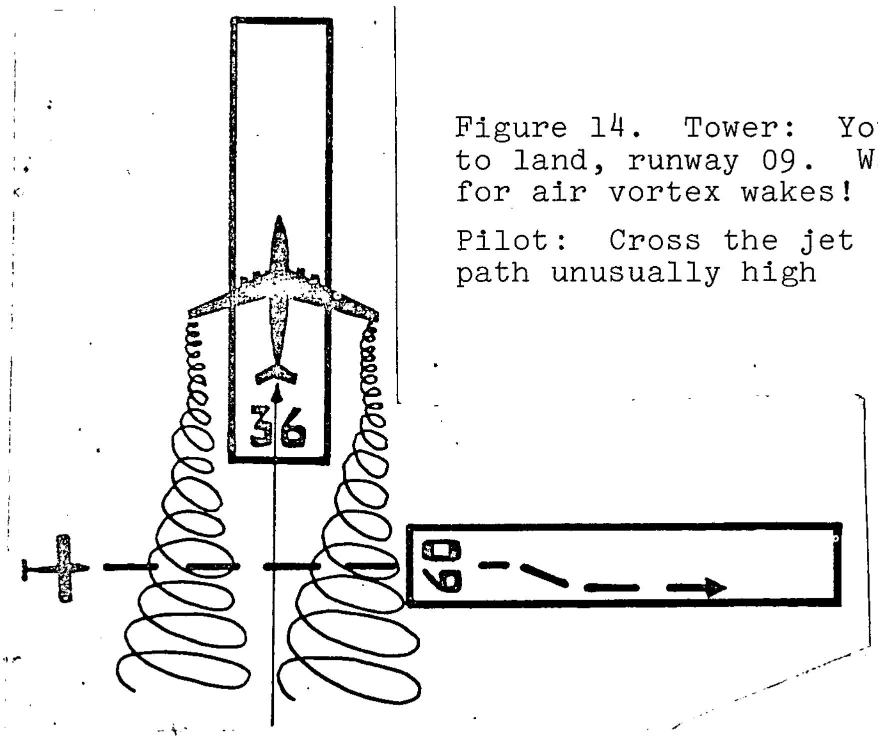


Figure 14. Tower: You are free to land, runway 09. Watch out for air vortex wakes! /17

Pilot: Cross the jet flight path unusually high

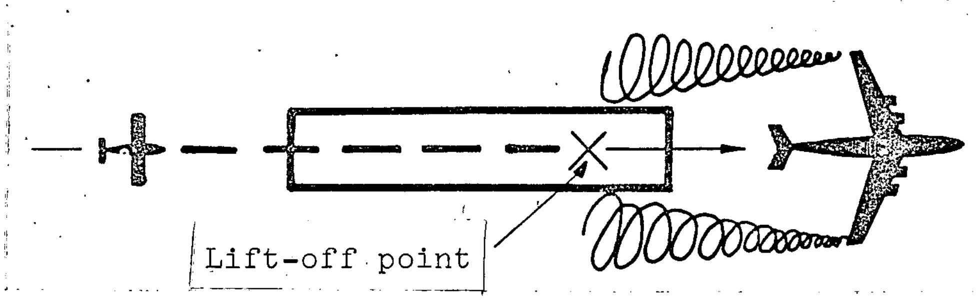


Figure 15. Tower: You are free to land. Be careful of air vortex wakes! A C-141 is taking off.

Pilot: Note the lift-off point and set down far before reaching it

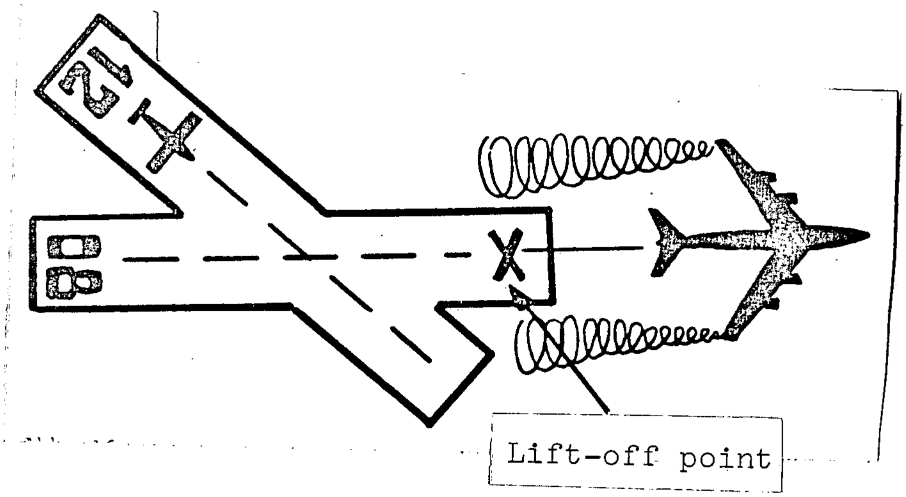


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Figure 16a. Tower: Free to land, runway 12. Watch for air vortex wakes! A C-141 is taking off on runway 08. (The tower holds back the landing clearance for a prescribed time in case there is a possibility of the flight paths crossing)

Pilot: Note the lift-off point of the jet. If it is beyond the crossing, continue the approach and land before it (Figure 16a). If the jet lifts off before the crossing, avoid flying below the flight path of the jet. Break off the approach unless you can land at a sufficient distance before the crossing (Figure 16b)

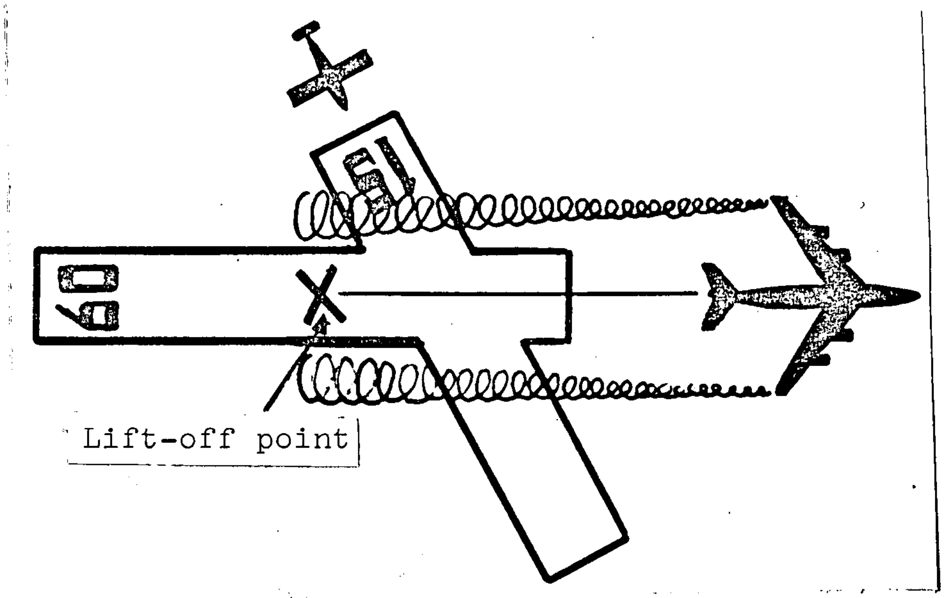

Figure 16b

Weight classes: /19

Weight classes:

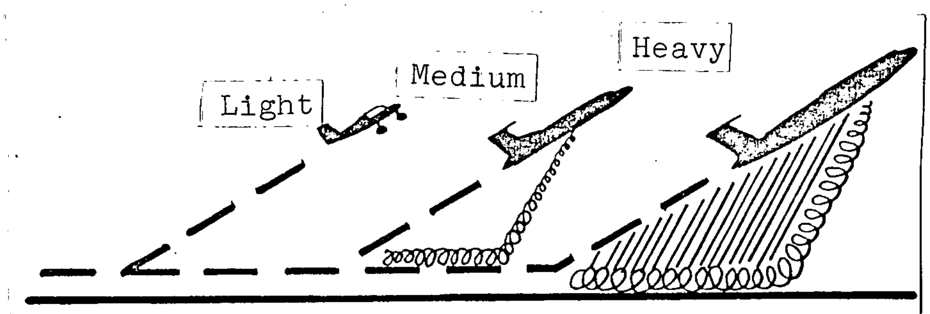

Figure 17a. Takeoff from the same runway

(Figure continued on following page)

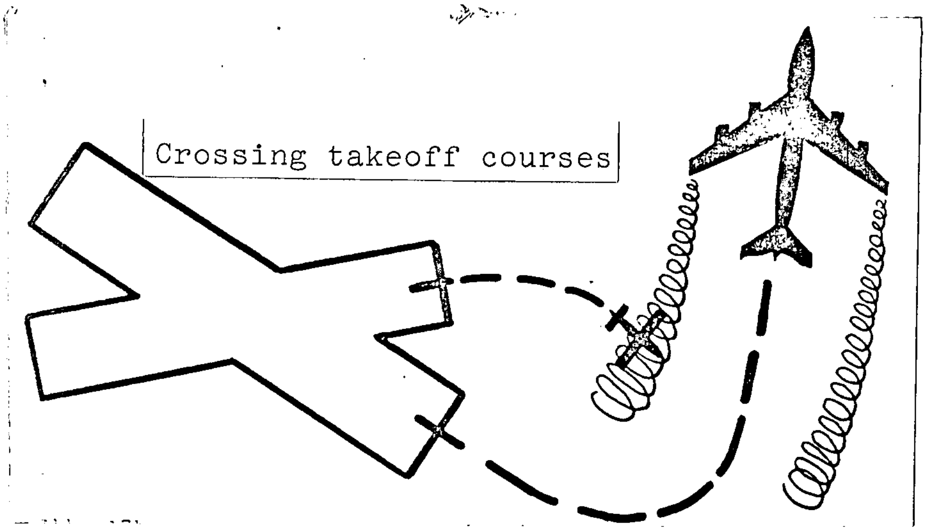

Figure 17b

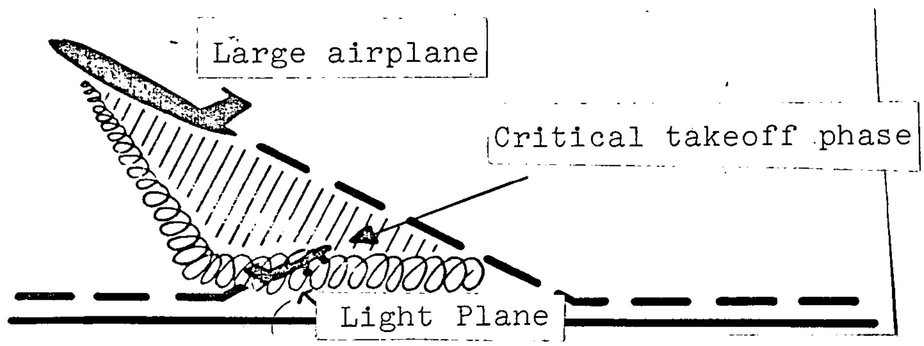

Figure 17c

Figure 17. Tower: The tower holds back on takeoff clearance for a prescribed time for the same runway or for parallel runways separated by less than 2,500 feet, and in any other situation in which crossing of the flight path appears possible. /20

Pilot: Note the liftoff point of the jet and lift off before this point. Climb above the flight path of the heavy jet until turning away from its vortex wakes (Figure 17a). Avoid following a course which would lead below and behind the flight path of a heavy jet (Figure 17b). Be careful on takeoffs which could lead to an encounter with air vortex wakes (Figure 17c)

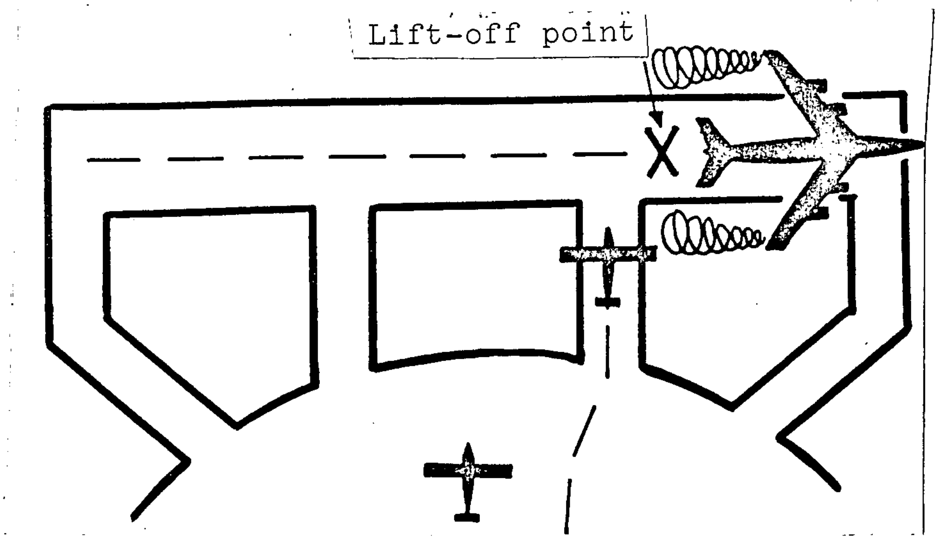

Figure 18. Tower: The tower holds back on takeoff clearance for a prescribed time for takeoffs from intersections, if a large jet has taken off on the same runway.

Pilot: Watch out for jets taking off! When takeoff clearance is given, avoid a following course which crosses below the flight path of a heavy jet

VFR commercial flight (altitude or flight level plus 500 feet) /21

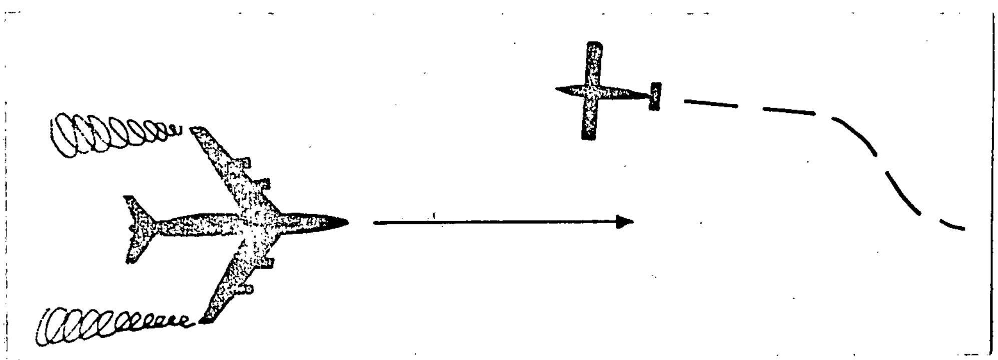

Figure 19. Tower: The tower has no part here.

Pilot: Avoid flying below and behind the path of a heavy jet. If you see a jet above you on the same or opposite courses, turn aside, preferably upwind!

Special Flight Safety Measures to Avoid Air Vortex Wakes

The air traffic controllers had hoped that, with the use of larger airplanes and their higher provision of seats, the air traffic which had been growing heavier from year to year would no longer increase at the previous growth rate. Thus, the future seemed somewhat easier! To be sure, a "Jumbo" can provide more than twice as many passages as an ordinary jet plane. All well and good, but they brought no easing of jet flights. Quite the opposite.

For one thing, the "Jumbos" gave the flight controllers here and elsewhere new procedures for performing air traffic control. They were forced to do this by the air vortex wakes pro- /22
duced by the heavy aircraft.

The American air travel authority FAA (Federal Aviation Administration) was the first to introduce new air traffic control procedures for the heavy jets. In the German Federal Republic, the Federal Flight Safety Office (BFS) published almost identical procedures for the German flight control centers. The latter are of great interest, particularly for all pilots, whether they are sport fliers or carry four "rings" of pistons. They could already have taken something from the illustrations on the preceding pages. But now to the special flight safety measures:

a) A time separation of at least 2 minutes is to be maintained between the landing of a large plane and an airplane landing after it on the same or a crossing or parallel runway.

b) A time separation of at least 2 minutes is to be maintained between a landing large plane and a plane taking off after it on a crossing runway.

c) A time separation of at least 2 minutes is to be maintained between takeoff of a large plane and a plane landing after it on a crossing runway.

d) A time separation of at least 2 minutes is to be maintained between takeoff of a large plane and takeoff of a plane on the same, or a parallel or crossing runway.

e) If a plane takes off behind a large plane from an intersection on the same runway, the takeoff run must not begin before three minutes after lift-off of the large plane.

f) Taxiing planes which are behind a taxiing large plane are to be sent a warning, such as: "Be careful, you are taxiing behind a B-747."

Comment: At present, the B-747 and the Lockheed C5A are in the category of large planes. /23

g) The BFS has also published the instruction that, when takeoffs and landings occur within two minutes behind a jet plane with a maximum takeoff weight of more than 150,000 kg, a warning of possible air vortex wakes must be transmitted, and the position of the heavy jet plane must be described. For instance: "Number two to land behind B-707, one mile final, caution, wake turbulence."

Comment: The following aircraft, among others, now have maximum takeoff weights over 150,000 kg: B-707, DC-8, DC-10, C-141, VC-10, Ilyushin IL-62.

h) In movement control by radar, a separation of at least 5 nautical miles must be maintained if a plane is directed with radar so that it is flying directly behind a large plane.

Conclusion

We have attempted to show what dangers to air traffic can be caused by air vortex wakes. These dangers must not be underestimated, even for experienced pilots. The recent studies of the American air travel authority, FAA, have shown that in various accidents between 1966 and 1968 air vortex wakes were always a decisive cause, if not the sole cause. In these accidents, a total of 62 people were killed or injured. (FAA report: The Killing Dervishes.)

There are still no on-board or ground-based installations to spy out the invisible air vortex wakes, follow their movements, and measure their strength. As long as these installations are lacking, the best defense is a comprehensive knowledge of the occurrence, spread, and strength of air vortex wakes. Many rough flights, many rough takeoffs, and not least, accidents, could be avoided in this way.

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